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COMPARISON OF SIMPLIFIED AND ADVANCED BUILDING SIMULATION TOOL WITH MEASURED DATA.

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ABSTRACT

In the future building design must progress to a format where CO_2 neutral societies are optimized as a whole and innovative technologies integrated.

The purpose of this paper is to demonstrate the problems using a simplified design tool to simulate a complicated building and how this may not give sufficiently good results in terms of actual performance of the real building. This is illustrated by example of Viborg Town Hall using a simplified Danish tool Be10 and a dynamic Building Simulation Programme IES-VE. The model is evaluated based on actual weather data. In addition, IES-VE is evaluated using a Monte Carlo simulation in order to evaluate the confidence level of the models' accuracy for Viborg Town Hall.

INTRODUCTION

The future will demand implementation of CO_2 neutral communities, the consequences being a far more complex design of the whole energy system, since the future energy infrastructures will be dynamic and climate responsive systems. When designing CO_2-free societies rather than only single low-energy buildings it will in many cases be more economical to produce for instance hot water at central locations rather than local in the building. This is because in most of the cases few low-level temperature resources are available for a reasonable cost for the local buildings. To heat water at low temperatures using oil, natural gas or electricity is from an energy efficiency point of view wasting of resources. In these cases, District Heating (DH) plays an important role in Denmark since it covers 62% of the heating demand (Christensen et al., 2012). By using low-temperature DH, one of the advances is that these low temperature level heat sources are CO_2 neutral or only result in little CO_2 emission, and that the cost is much lower as a result of the lower specific costs for large plants.

Designing CO_2 neutral communities is a design process informed by multidisciplinary knowledge, where different software plays an important role. Numerous simulation programs from different kinds of engineering fields (indoor climate, energy balance, life cycle assessment etc.) exist today or consultants make their own programs in Excel or similar to solve specific tasks. Commercial players concentrate these programs on platforms with different plug-ins; but since they are not developed on a common foundation, aimed at integrated design, the programs lack from being to interoperate.

Danish Building regulation

In Denmark, the 2010 edition of the Danish Building regulation (BR10) (Energistyrelsen, 2010) has set targets for the years 2015 and 2020 for the permissible energy consumption for buildings in the process of creating CO_2 neutral communities in the future, Table 1. This makes it possible for the building industry to use these targets as benchmarks for advanced buildings. The energy frame consists of primary energy demands for heating, cooling ventilation and domestic hot water. In 2020 the energy frame will demand the use of energy supply systems.

Table 1
Energy frames from the current and future building codes

Energy Frame 2010 [kWh/m^2/year]

Term	Dwellings	Other buildings
Requirement	52.5 + 1610/A	71.3 + 1650/A
Low energy class 2015	30 + 1000/A	41 + 1000/A
Low energy class 2020	20	25

BR10 prescribes the use of primary energy factors, representing the relationship between primary energy and end-user energy requirement. The primary energy factors for the different energy types used in buildings can be found in Table 2.

In order to control that the Danish Building regulation is fulfilled a simple Danish design tool Be10 (SBI, 2011) has been developed to calculate the energy performance and ensure that the energy requirements have been met – see Methodology section. The simulation has to be done prior to completion, and is intended to verify that the building is constructed as proposed at the building permit approval. The labelling is conducted instantaneously after construction (Energistyrelsen, 2012).

Table 2
Current and future primary energy factors

Primary energy factor [-]

Energy frame	**Heat from district heating**	**Other heat resources**	**Electricity**
BR10	1,0	1,0	2,5
Low energy class 2015	0,8	1,0	2,5
Low energy class 2020	0,6	1,0	1,8

However, recent studies have shown large deviations between predicted and measured energy performance in buildings leading to a suspicion of the mandatory energy performance calculation tool Be10 producing inaccurate results. The deviations make it doubtful whether the political goal of achieving the necessary reductions needed for supplying the energy consumptions in buildings with only renewable energy in Denmark can be met by 2035. An investigation into the accuracy of calculated energy performances along with assessment of indoor environments is conducted and put into a design perspective, based on both academic theory and empirical data.

Problem statement

Building design must evolve from today's practice – where the individual building parts are optimized separately – into a future where CO_2 neutral societies are optimized as a whole, and the individual buildings, including all installed systems, is optimized by integrating innovative technologies that will furthermore make the building itself an active part of the total energy system.

The purpose of this paper is to demonstrate the problems using a simplified design tool and how it may not give sufficient good results in term of actual performance of the real building. This is illustrated by example with Viborg Town Hall how the simplified Danish tool Be10 and the dynamic Building Simulation Programme (BSP) IES-VE (IES, 2013) perform compared with measured data. The illustration of the calculated thermal indoor climate using IES-VE shows the strength of using a BSP with a detailed model to show rooms with possibility for overheating. This is not possible with a program like Be10.

Another purpose with this paper is to demonstrate the use of the methodology established in the European Standard EN 15.603 (DS/EN, 2008) as an indicator of the BSP tool IES-VE accuracy. The standard outlines the validation procedure for obtaining higher confidence levels in building calculation models. A comparison of measured energy use with calculated results, obtained in an advanced simulation tool, is conducted based on the prescribed validation procedure using probabilistic inputs subjected to Monte Carlo Simulations.

Finally the paper also illustrates the complexity of transforming the model for the complicated building Viborg Town Hall from AutoCAD to a useable IES model.

BUILDING – VIBORG TOWN HALL

The development in this paper is exemplified with Viborg Town Hall, used as calculation object throughout, Figure 1. The conclusions from the study are of course more generic, and applicable to a wide range of commercial buildings.

The Town Hall was officially opened on the 30th of September 2011. The 19.400 m^2 are distributed on 5 storeys and a basement for installation and archives. The office building has 885 working places and has cost approximately 40 million €, 2 million € below budget.

Figure 1 Viborg Town Hall from the outside

Designed by Henning Larsen Architects and COWI, the building fulfils the Danish 2015 energy requirements of 50 kWh/m^2 year-1, achieved by use of hybrid ventilation, photovoltaic, three layer energy windows and a very tight building envelope.

The building envelope consists of windows with a U-value of 0.9 W/m^2•K, a metal covered facade with a U-value of 0.13-0.19 W/m^2•K, a ground deck with a U-value of 0.12 W/m^2•K and a roof with 0.12 W/m^2•K. An infiltration of only 0,4 l/s pr. m^2 was measured during the mandatory Blower Door Test, which is significantly lower than the BR10 requirement of 1.5 l/s pr. m^2 or the passive house requirement of 0.6 l/s pr. m^2 (Passivhus.dk, 2013).

The southern windows are coated with solar shading to reduce the solar heat load and thereby the cooling demands during the summer. The façade is furthermore equipped with static shading devices, which reduces the direct solar radiation and prevents glare.

The photovoltaic are placed on the roof of the bicycle sheds and is expected to have an annual electricity production of approximately 85,400 kWh.
The building uses the stack effect in the atrium in the middle of the building, shown in Figure 2, as the driving force for the natural ventilation, ventilating all rooms except the mechanical ventilated meeting rooms, basement server room and the fifth floor. The rooms are supplied with fresh air through automatic louvers placed above the suspended ceiling. The mechanical ventilation has heat recovery and is preheated or cooled by the supply system. The natural- and the mechanical ventilation are controlled by feedback from temperature- and CO_2 measurements in the buildings.

Figure 2 The atrium of Viborg Town Hall

The buildings' HVAC system consists of district heating supplied convectors for heating and thermo active slabs (TABS) for heating and cooling. Four adsorption pumps fuelled by district heating and an electrified heat pump both of which are able to produce heating and cooling supply the TABS. The specific heat capacity of the TABS can store and release heat depending on actual needs, thus creating less fluctuation in the temperatures over time. An aquifer is furthermore used to cool down the building and stores excess heat in the ground water for later use, see Figure 3.
The supply system to the building works on three different temperature levels; high for heating the convectors, medium for heating the TABS/ventilation and cold for cooling TABS and ventilation air. All three systems have a buffer tank to even the loads and ensure stable supply conditions as well as optimal operating conditions for the supply units.
The buildings' Building Management System (BMS) ensures the supply is handled in the most efficient way, measured either by the lowest energy consumption, the lowest price or the lowest CO_2-emmision. This feature will become very relevant when the energy marked opens for real-time prices of heat and electricity.

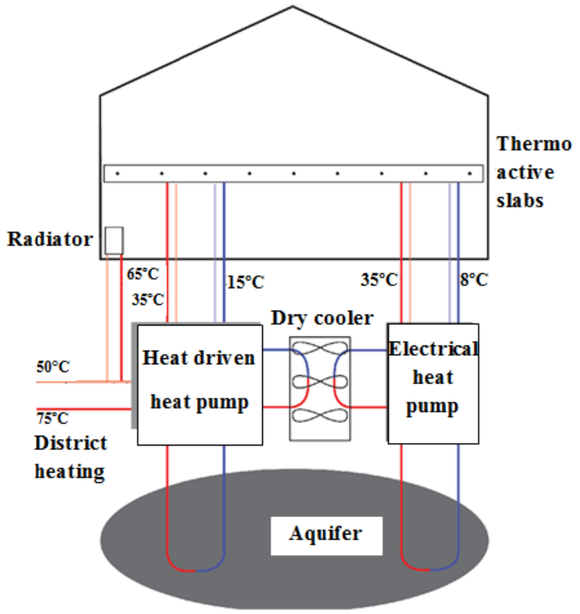

Figure 3 Principe diagram of supply system (Viborg Kommune, 2010)

Best Energy

Viborg Town Hall is part of the European Union financed Best Energy Project. The objective of the project is to improve the energy efficiency by using Intelligent Communication Technology (ICT) to control and evaluate the energy consumption. Projects in Portugal, Spain, Czech Republic and Germany are also involved in the project, which strive to reduce the energy consumption by 12%, compared to the predicted energy consumption if no energy reduction measures are applied.
In order to control and evaluate the energy consumption a large amount of secondary meters are installed, separating Viborg Town Hall from regular construction projects as it is possible to distinguish between electricity used for building services like artificial lighting, pumps, ventilation and cooling and electricity used for appliances etc. The temperature and CO_2 concentration in the different thermal zones

of the building are logged in the BMS system along with weather data. These huge amounts of data make Viborg Town Hall a very suitable case for the investigation of this paper.

Model geometry

The model geometry has been done in Autodesk Revit Architecture (Revit), a 3D Building Information Modelling (BIM) tool, and from there exporting the model to IES-VE. When the geometry and thermal zones are designated in IES-VE, the detailed energy simulation can commence. By creating the entire building in the simulation, a lot of simplifications and potential errors are eliminated, such as representative rooms. One of the drawbacks of making a full-scale model is the time consumption, especially when the subject building is as complicated as Viborg Town Hall.

Figure 4 Geometry creation steps – Revit

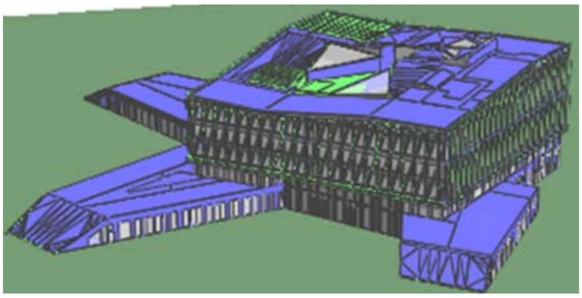

Figure 5 Geometry creation steps – IES-VE

As input for the model COWI has provided several floor and elevation plans, accompanied by digital 2D floor plans in AutoCAD format. In Revit it is possible to create levels according to the different floors of the proposed building, and insert the floor plans on the corresponding level. The roof of Viborg Town Hall has been quite challenging to model as it has numerous different slopes and heights, thus making an import with a 2D plan void. Instead the roof and skylights were created with the correct elevations, Figure 4 (a total of 26 different elevations were necessary after simplifications.).

With the building envelope finished, the interior space is divided into thermal zones that correspond to the zoning in the ICT system, thus enabling easy comparison of the model and reality. The geometry is finally imported into IES-VE, where the aforementioned wall and window types are applied the correct materials and data, Figure 5.

Weather data

The model is evaluated based on real weather measurements, air temperature, relative humidity, wind direction, wind speed and the global solar irradiance. Despite the presence of a weather station on the roof of Viborg Town Hall, measurements on-site showed an overestimation of the exterior temperatures during the daytime, when compared to weather measurements from the Danish Meteorological Institute (DMI).

Measurements from the DMI weather station Foulum, located 10 km from Viborg Town Hall were therefore acquired and used instead of the on-site measurements. Since only the global irradiance is given in the Foulum measurements, the diffuse solar irradiance is determined by using the Orgill and Hollands correlation between the diffuse and global irradiation subject to the clearness index (Duffie, et al., 1991).

Since the building has not been in operation for a full year, a full year is simulated using the Copenhagen DRY weather file.

METHODOLOGY

The reported investigation has two aims:

- to clarify the contradiction between the calculation from a simplified tool Be10, a dynamic Building Simulation Programme IES-VE and measurements
- to illustrate an alternative simulation of energy consumption using Monte Carlo Simulation with confidence interval.

Building Simulation Tool – Be10

The energy labelling of buildings in Denmark according to the. Danish Building Regulations BR10 (Energistyrelsen, 2010) is calculated by legal requirement through the tool Be10, developed by the Danish Building Research Institute (SBI, 2011). Be10 includes both static parameters (heat transfer coefficient, light-transmittance and infiltration) and non-static parameters (e.g. user behaviour and function of building) in the energy performance calculation. It is, however, not possible to change the Danish Design Reference Year (DRY) weather data. Be10 uses the simplified method mentioned in the Energy Performance Building Directive (EPBD) (EU, 2010) for calculating the energy rating and considers the interior of the building as a single thermal zone. Due to its spreadsheet input approach, it furthermore simplifies the building envelope described by surface areas facing different orientations. The energy performance is calculated based on monthly steady state calculations (SBI, 2011).

Building Simulation Tool – IES-VE

Integrated Environmental Solutions (IES, 2013) has developed the BSP IES-VE (Virtual Environment), which consists of a number of integrated building

performance analysis applications. The program provides three-dimensional geometric representation of the building in which building elements and zones can be described in detail.
The program is validated for heating, cooling and building envelope calculations by ASHRAE 140-2007, dynamic simulations by ISO 13791:2012 (ISO, 2012) and compliance test of the energy performance in the United Kingdom documented by a TM33 test. It furthermore features an application for calculating BREEAM credits. For geometry modelling the tool supports the open source format gbXML (green building XML), thus allowing for geometry import from other modelling programs such as ArchiCAD, Autodesk Revit and Google SketchUp.

Monte Carlo Simulation

The method for validation of building energy models described in European Standard EN 15.603 (DS/EN, 2008) will be used on the model of the case study Viborg Town Hall in order to evaluate the confidence level of the models' accuracy. The method prescribes a procedure for comparing the calculated result with the actual energy use. The actual energy consumption is obtained as shown in Table 2. The calculated energy consumption is obtained by using input data as close to reality as reasonably possible not only for the building, but also for the climatic and occupancy data, resulting in a tailored energy model as described in Table 2. The normal distribution is used for e.g. the internal temperature as it is expected to have a symmetrical deviation from the projected mean value. The logarithmic normal distribution is used for e.g. the thermal transmittance as EN 15.603 estimates it is more likely that U-values have a standard deviation with a spread larger to the "positive" side than the "negative". EN 15.603 prescribes methods for collecting climatic data and mean values for air infiltration and ventilation, internal heat sources and hot water use. Input procedures for the remaining parameters can be achieved through freedom of method.
Each input parameter is subject to an uncertainty calculation as the design data might not be exact. A probability distribution and standard deviation will therefore describe likely deviations to the design specification.
Based on the different distributions, mean values and standard deviations for the uncertain input data are different samples of Viborg Town Hall. The samples are created by a random number generator in Microsoft Excel and imported into building energy model, so called Monte Carlo Simulation.

The following Excel functions are used in to generate inputs: example:

For normal distributions:

$$Input = NORMINV(RAND(\quad); \mu; \sigma) \tag{1}$$

For logarithmic distributions:

$$Input = \mathrm{LOG}INV(RAND(\quad); \mu; \sigma) \tag{2}$$

The Monte Carlo Simulation is used to create a confidence interval of the mean value $\bar{x}$ at the probability P when N samples are made for the energy consumption by applying the following formula:

$$\delta_x = \frac{s(x)}{\sqrt{N}} \cdot T(P, N-1) \tag{3}$$

Where the energy consumption is assumed to be normal distributed and *s(x)* is:

$$s_x = \sqrt{\frac{\sum_i (x_i^2) - N \cdot \bar{x}^2}{(N-1)}} \tag{4}$$

The model will become validated if the measured energy consumption is within the confidence interval created by the Monte Carlo Simulation of the Viborg Town Hall model.

DISCUSSION AND RESULT ANALYSIS

As the design of Viborg Town Hall started prior to 2010 and the development of Be10 from 2010 (SBI, 2011), the earlier version Be06 from 2006 has been used for the authority approval. As both the measurements and the IES-VE results are based on actual weather data the Be06 heating and cooling results have to be adjusted, since the results of Be06 are based on the Copenhagen DRY weather data.
In the text terminology such as the calculations, refer to the IES-VE simulation unless stated otherwise.

Presentation of the results

With the tailored energy model, a number of simulations of the energy consumption have been made. For a full year simulation directly comparable to Be06 a simulation using the standard weather file of Copenhagen DRY has been conducted. Secondly, a simulation using local weather data from Viborg has been conducted in order to evaluate the accuracy of the energy simulation when comparing to measurements conducted on-site in the period November 1st 2011 to April 30th 2012. The indoor environment has been evaluated based on the full year DRY simulation as the summer months are assumed to be the greatest threat to the indoor climate in Viborg Town Hall.

Benchmark between Measured and Calculated

The actual energy consumption measured at Viborg Town Hall is benchmarked with the results from the tailored energy models made in IES-VE and Be06 in Figure 6. The Be06 results are comprised of the calculated consumption of Domestic Hot Water (DHW), cooling from IES-VE, since the DHW from IES-VE is based on actual measurements, and Be06 doesn't indicate a need for cooling of the servers. The heating and cooling demands have been estimated based on the degree-day method (DANVAK, 2006) with degree-day factors supplied by COWI.

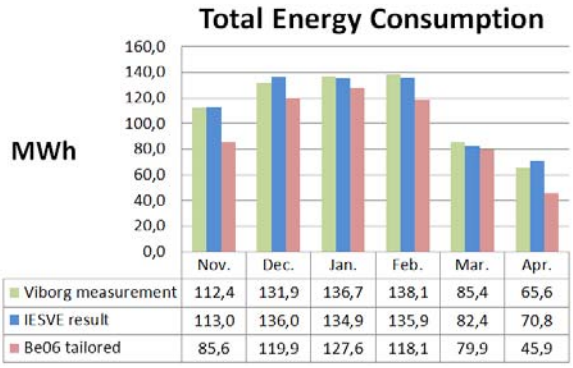

Figure 6 Benchmark between actual and calculated energy consumption

The energy consumptions seem to be strongly correlated, which ensures confidence in the model. The total energy consumption in the 6 month period from November 1st 2011 to April 30th 2012 is 670 MWh and 673 MWh for the measured and IES-VE simulation results respectively, a deviation of:

$$\frac{670MWh-673MWh}{670MWh}=-0{,}44\ \%.$$

The tailored Be06 model gives a total energy consumption of 577 MWh, a deviation of 13 % below the measured consumption.

It can be seen that the results in both cases are very close even for the simple model Be06. However, one of the reasons for the good Be06 can be due to that positive and negative values eliminate each other, especially the domestic hot water seems to be overestimated.

With a very decent recreation of reality for the total energy performance of IES-VE, investigations into the individual posts are conducted.

Validation of model using Monte Carlo Simulation

The validation period is from November 1st 2011 to April 30th 2012.

Ten batches of the Viborg Town Hall model are created and simulated in accordance with the procedure described in the Methodology of Investigation chapter in order to create the confidence interval used to determine the validity of the model of Viborg Town Hall made in IES-VE.

The Student coefficient *T(P=0,95;N-1=10-1) = 2,306* has been used for the ten batches. This means that if another batch simulation would be done the probability of the result lying within the created confidence interval will be 95 %. The mean value of the Monte Carlo Simulation of 10 batches is 655 MWh, which has a standard deviation, s(x), of 34,4 MWh. Equation 3 gives the confidence interval:

$$\delta_x=\frac{s(x)}{\sqrt{N}}\cdot T(P,N-1)=\frac{34{,}4MWh}{\sqrt{10}}\cdot 2{,}306 \qquad (5)$$
$$=25\ MWh$$

The confidence interval of the model is thereby as illustrated in Figure 7:

655 MWh ± 25 MWh, 630 MWh – 680 MWh

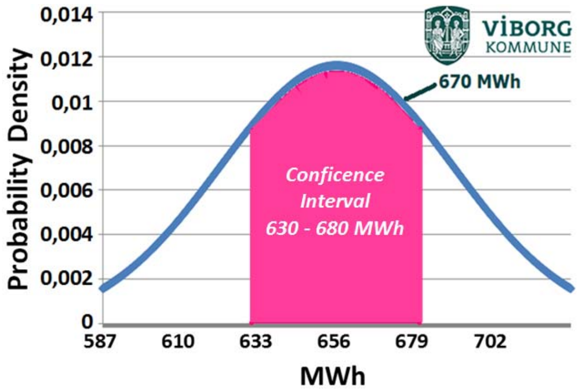

Figure 7 Confidence interval and probability density N(655;25), created from Monte Carlo Simulation of IES-VE model of Viborg Town Hall

Figure 7 shows the measured energy consumption, 670 MWh, is within the confidence interval, and the model is thereby validated in accordance with the EN 15.603. The validation test is also performed for each single month as illustrated in Table 3. The measured energy consumption is for all months except April within the confidence interval, and thereby passes the validation test.

Table 3
Validation test for total energy requirement

Month	Confidence Interval [MWh]	Measure-ment [MWh]	Validity?
November	109-118	112	YES
December	130-141	132	YES
January	108-142	137	YES
February	105-146	138	YES
March	82-90	84	YES
April	71-79	66	NO
TOTAL	630-680	670	YES

The validation is based on the total energy consumption, and hence does not evaluate the validity of the individual energy consumption as heating, DHW, cooling, artificial lighting, building operation and the power production from the PV panels. In order to make sure the validation does not rely on inaccurate individual energy consumptions, coincidentally giving a good estimation of the total energy consumption, the individual energy consumptions are evaluated individually for all months of the validation period from November to April – however only Heating is shown in this paper.

Heating

The measured energy consumption is within the confidence interval for each month except the first whole month of operation, November 2011, where the energy consumption is much lower than expected according to Table 4. Almost every variable subject to the Monte Carlo Simulation has an influence on the heating requirement showing the strengths of the validation procedure for heating.

Table 4
Validation test for heating

Month	Confidence Interval [MWh]	Measure-ment [MWh]	Validity?
November	67-76	52	NO
December	82-94	84	YES
January	60-94	91	YES
February	71-112	99	YES
March	42-51	49	YES
April	35-43	37	YES
TOTAL	389-437	412	YES

Indoor Environment Analysis

The illustration of the calculated thermal indoor climate is not supposed to be a comparison. The reason for this is that there were not sufficient data available for the temperature level and the CO_2 level to make a proper evaluation. Instead, it is the intention to show the advantage of using a BSP with a detailed model to show how an overview for all the rooms can be illustrated for overheating, CO_2 concentration, etc. In a design process, this can be used to redesign specific solutions in order to develop a better and more energy efficient building. This is not possible with a simplified program like Be10.

The indoor environment is evaluated by the percentage of hours in the occupied period outside the desired temperature range from 20ºC – 26ºC based on the Danish DRY weather file. Altogether 53 rooms have been analysed to get an overview of thermal indoor climate. On Table 5 is only a selection of nine rooms showed as an illustration for the summer months May to August.

The mechanical ventilated meeting rooms (*M xx*) all have a very good thermal indoor environment, as only one has hours outside the desired range when occupied, topping in June at 4,2 %. The mechanical ventilated Multi Hall and cantina also have thermal indoor environments clearly within the given ranges.

Contrary to the meeting rooms, the naturally ventilated open plane offices (*TD xxx*) have problems with the thermal indoor environment in several of the 35 open plane offices. The problems are almost entirely due to overheating in the summer season where the zones experience temperatures over 26ºC. The open plane offices placed on the 4th floor (*TD x4x*) generally have the most overheating problems when compared to the other floors, even though the ground floor does not perform much better.

Note that potential summer vacation is not included in the model, which means Viborg Town Hall is presumed fully occupied in June, July and August during holiday season.

Table 5
Selection of thermal Indoor environment analysis. The number indicates the percentage of hours outside 20ºC – 26ºC when the rooms are occupied. A red colour indicates temperatures are above 26ºC

ROOM	Ventilation	May	Jun.	Jul.	Aug.
M14	Mech.	0,0	0,0	0,0	0,0
M15	Mech.	0,0	0,0	0,0	0,0
M16	Mech.	0,0	0,0	0,0	0,0
M17	Mech.	0,0	0,0	0,0	0,0
M18	Mech.	0,0	0,0	0,0	0,0
TD 212	Natural	3,6	5,5	1,3	2,1
TD 312	Natural	2,0	4,5	1,3	2,1
TD 312	Natural	0,0	0,0	0,0	0,0
TD 311	Natural	9,5	14,8	17,2	17,4

The indoor environment has also been evaluated based on the CO_2 concentration above 900 ppm during occupancy. Regarding the CO_2 concentration, it was found that the ventilation successfully removes all unwanted pollution at all times of occupancy, thus eliminating any further investigation.

CONCLUSION

The investigation showed the energy consumption can be predicted more precisely when using full scale dynamic simulations compared to the mandatory shoebox procedure of Be10. The assessed period gave in the 6-month period from November 1st 2011 to April 30th 2012 670 MWh for the measured and 673 MWh for the IES-VE simulation. The tailored Be06 model gives a total energy consumption of 577 MWh, a deviation of 13 % below the measured consumption. Both results are very close to the measured data. Be06 is also close, even though it is a very simple model; however the reason for this can also be that positive and negative values eliminate each other, for instance domestic hot water.

The model was validated according to EN 15.603 validation procedure as the measured energy consumption of 670 MWh lies within the confidence interval 630 MWh – 680 MWh created by the Monte Carlo Simulation for the entire validation period of six months. EN 15.603 recommends looking at measurements conducted three years or later than commissioning, thus excluding the running-in period, an approach not possible for a building as new a Viborg Town Hall. The investigation of the model validation has as a consequence of this gone into further detail than the procedure dictates. The energy consumption of the six months individually has been examined and all months except April lie within the confidence intervals. On an overall level the energy simulation model is thus fairly close to reality, also when validating individual months.

When using more advanced tools such as BSP, indoor environment can be assessed on room level resulting in far more accurate predictions of possible critical areas early in the design process, thereby avoiding potential uncomfortable zones. Initiatives such as these will become even more relevant as demands from both authorities and building proprietors continues to increase.

BSP is becoming more and more compatible with BIM tools creating a smooth transition between the technical disciplines related to building design, thus making it suitable for the holistic approach of the Integrated Design Process. This is presumed to increase as the demand for BIM rises even further. The increased levels of detailing has the benefit of making design possibilities more apparent for the designer, possibilities that could otherwise be missed when using more simplified calculation methods.

NOMENCLATURE

RAND() = random generator used to produce the probability of each input

$s(x)$ = estimate of the standard deviation of the samples x

$T(P,N)$ = Student coefficient for having the next simulation result within the confidence interval with probability P

$\bar{x}$ = estimate of the mean

μ = mean value of the input data

σ = standard deviation of the input variable based on the guidelines from (DS/EN, 2008)

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